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Integration of Thermal Energy Harvesting in Semi-Active Piezoelectric Shunt-Damping Systems

MICHAł LUBIENIECKI[1,2] and TADEUSZ UHL[1]

1.—Department of Robotics and Mechatronics, AGH University of Science and Technology in Cracow (AGH-UST), al. Mickiewicza 30, 30-059 Cracow, Poland. 2.—e-mail: lubienie@agh.edu.pl

The opportunities to energize a broad range of devices by use of energy available almost anywhere and in many forms are almost unlimited. A major advantage of energy harvesting is the manufacture of small autonomous electronic devices with no need for power supply and maintenance. Shunt damping circuits, although unfavorably affected by the size and mass of bulky coil inductors, started to base on synthetic inductors losing their passivity. In this paper we report a study of the feasibility of powering shunt damping circuits by use of thermal energy otherwise irrevocably lost from a bearing. The heat generated in the bearing is converted thermoelectrically into electric energy which is then used to power synthetic inductance circuitry. We show that the power demand of such circuit can be satisfied by use of a thermoelectric generator paired with a moderately loaded bearing.

Key words: Energy harvesting, piezoelectric shunt damping, smart bearing, autonomous devices

List of Symbols

d_0	Nominal bore diameter of a bearing, m
F_r	Radial load, N
F_a	Axial load, N
I	Current in an equivalent electric circuit, W
I_{source}	Power loss in a bearing, W
ε	Joule's heat distribution variable
L	Length, m
A	Area, m^2
N_{pair}	Number of thermocouples in a TEM
n_{RPM}	Speed of rotation—revolutions per minute, min^{-1}
R_C	Thermal resistance of a rotating shaft resulting from convective heat transfer, K W^{-1}
R_{TEG}	Temperature-dependent resistance of a thermoelectric generator, K W^{-1}
R_{HS}	Heat sink thermal resistance, K W^{-1}
R_{PART}	Insulating partition thermal resistance, K W^{-1}
R_{HSTR}	Thermal resistance of structural components of a system, K W^{-1}
R_{CNV}	Thermal resistance connected with natural convection, K W^{-1}
R_{CNT}	Contact thermal resistance, K W^{-1}
R_{HS}	Thermal resistance of a heat sink, K W^{-1}
R_L	Load impedance, V A^{-1}
R_{lLINK}	Thermal resistance of a thermal bypass, K W^{-1}
N_{fins}	Number of U-shaped fins of a heat sink
T	Temperature, K
T_{amb}	Ambient temperature, K
α	Seebeck coefficient, V K^{-1}
τ	Thomson coefficient, V K^{-1}

Superscripts

c, h	Cold and hot junctions, respectively, of a thermocouple
T	Temperature-dependent value
EL	Indicates electrical property of the TEG module
TH	Indicates thermal property of the TEG module

Subscripts

0, 1 …	Consecutive element numbers
E	Value at electrical domain
av	Mean value

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INTRODUCTION

The shaft support, besides its obvious function, serves as a force-transfer path between shaft-mounted components (e.g. meshing gears) and the machine housing or foundation. Mechanical interactions give rise to structure-borne noise or vibrations. No attempt has been made to combine semi-passive piezoelectric shunted circuits (i.e., those with synthetic inductance) with thermal harvesting sources in rotating machines. An argument for such a combination would be that having addressed the vibrations in close proximity to the bearing, fewer vibration transfer paths have to be monitored.[1] Furthermore, each bearing, irrespective of its type, load, and the lubricant used, generates heat as a result of rolling friction, sliding friction, oil drag, and other factors contributing to the overall friction of the bearing. Moreover, rotating machinery is characterized by a periodic disturbance with a fundamental frequency proportional to the speed of rotation of the machine; this is favorable for shunted piezoelectrics, which must be tuned to the frequency of operation. If the frequencies are not known in advance, adaptive shunts are applicable.

In this paper we report a study of the feasibility of using an autonomous piezoelectric damper located near a bearing of rotating machinery that is powered by thermoelectric generator, eliminating the need for an external power supply. The first section of the paper describes the idea of the autonomous damper. A model of a bearing is then presented, with experimental validation. Finally, the results of the analysis are discussed and conclusions are drawn on the basis of the research.

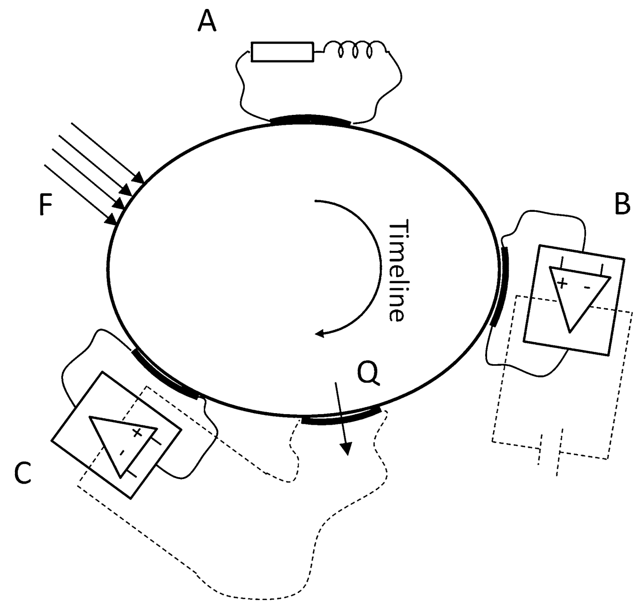

Fig. 1. Schematic representation of the evolution of shunt-damping systems: (a) passive, linear system; (b) semi-passive system; (c) proposed solution with restored passivity.

THE CONCEPT OF AN AUTONOMOUS VIBRATION DAMPER

The idea of damping vibration in a bearing housing by use of a piezoelectric stack has been discussed[2] and developed.[3] These authors showed that with actively driven and shunted piezoelectrics it was possible to achieve substantial vibration and noise reduction. However, to overcome the typical flaw of the shunt-damping technique, i.e., a bulky inductor with high internal resistance, the wound inductor should be replaced by an electronic circuit with the required electrical characteristics. This circuit must include a power supply. Several attempts have been made to introduce self-powered vibration dampers. The strain amplitude minimization patch (STAMP) damper was presented[4,5] as a self-powered shunt vibration controller. However, the performance achieved was worse than that of externally powered switched inductors. In a similar device comprising two piezoelectrics,[6] one acted as the energy harvester, powering the transistor gate, drives, and timing circuitry. Piezoelectric energy-harvesting devices are typically characterized by light coupling and are unsuitable for synergic combination with vibration dampers. To maintain self-sustainable operation, combination of a thermoelectric source and shunted piezoelectric patch has been proposed.[7] The evolution of shunt-damping systems is shown in Fig. 1.

Several types of synthetic inductor have been developed. The first constructions were based on operational amplifiers and have undergone substantial changes in performance throughout the years, mainly because of advances in electronics and the scale of integration. The important characteristic of a synthetic inductor is that despite a change in inductance the power consumption remains practically unchanged. The literature reports inductance differing from a fraction of henry to two henries, which is a typical range for shunted piezoelectric actuators working in the frequency range of a few to several hundred hertz. Testing of different synthetic inductors has shown power consumption to be 100–500 mW. Luo et al.[8] proposed construction of a synthetic inductor based on power electronics instead of operational amplifiers. As a result power consumption was reduced by an order of magnitude. Experimental tests showed power consumption was 11 mW for 1 H inductance, 100 kHz switching frequency, and a 5 V direct current (DC) bus. In this paper this is taken as the reference power consumption.

The idea of an autonomous vibration damper includes all passive shunt circuit topology except linear resistance and linear capacity, both of which are characterized by poor damping capabilities. To verify the correctness of the concept presented, the power of the thermoelectric generator coupled to a medium-sized self-aligning ball bearing was experimentally measured for a set of different speeds of

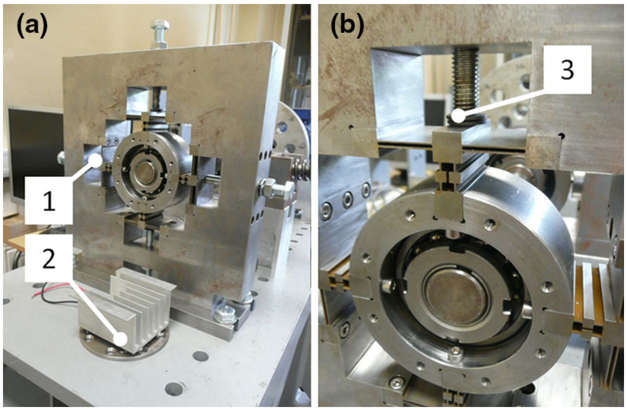

Fig. 2. The bearing used in this study (a) and close up of the inner ring and flexure joint (b). The piezoelectric stack elements (1) are preloaded by use of spring plates (3). The thermoelectric module (2) is mounted on the bearing cap (here dismounted).

rotation and constant radial loads. The power obtained was compared with the power demand of the synthetic inductors reported in the literature.

The bearing used in this study, with integrated piezoelectric and thermoelectric materials, is shown in Fig. 2. It consists of four flexural elements, analogous with other work,[1] supported by a piezo stack and preloaded spring plates on opposite sides. The bearing cap also serves as a mounting surface for the thermoelectric module with heat sink.

STUDY OF THE FEASIBILITY OF THE PROPOSED CONCEPT OF THE AUTONOMOUS DAMPER

To analyze the concept of an autonomous vibration damper under different operating conditions an equivalent model of the bearing was proposed. The general scheme of the bearing with the harvester is shown in Fig. 3.

A resistive network was chosen to introduce maximum generality to the model. For simplicity and because of interest in steady operating conditions the thermal mass (capacitance) has been omitted. Within the model equivalent circuit proposed one can identify two important characteristics of the circuit:

1. The bearing housing is thermally linked to the machine base but insulated from the bearing; additional heat sinks are required (R_{link} with infinite impedance)
2. The bearing housing is thermally insulated from the machine base and the heat source (i.e., bearing) and acts as a heat sink (R_{link} with zero impedance)

The equations for node voltages of the equivalent electrical circuit were obtained by modified nodal analysis. Together with constraint equations for the sources of current and voltage they create a set of complete equations (Eqs. 1–9) describing the thermal network.

$$T_1 = P_{\mathrm{loss}}(n_{\mathrm{RPM}}, F_{\mathrm{r}}, F_{\mathrm{a}}, T_1, B_{\mathrm{type}}, d_{\mathrm{o}}) - \frac{(T_1 - T_2)}{R^1_{\mathrm{CNT}}} - \frac{(T_1 - T_3)}{R^2_{\mathrm{CNT}}} \tag{1}$$

$$T_2 = \frac{(T_2 - T_0)}{R_{\mathrm{c}}(T_2, n_{\mathrm{RPM}}, d_0, L_{\mathrm{shaft}})} + \frac{(T_2 - T_1)}{R^1_{\mathrm{CNT}}} \tag{2}$$

$$T_3 = \frac{(T_3 - T_1)}{R^2_{\mathrm{CNT}}} + \frac{(T_3 - T_0)}{R_{\mathrm{CNV}}(T_3)} + \frac{(T_3 - T_4)}{R^3_{\mathrm{CNT}}} - \frac{(T_3 - T_7)}{R_{\mathrm{part}}} \tag{3}$$

$$T_4 = \frac{(T_4 - T_3)}{R^3_{\mathrm{CNT}}} + \frac{(T_4 - T_5)}{R^{\mathrm{TH}}_{\mathrm{TEG}}(T_4, T_5, N_{\mathrm{pair}}, A_{\mathrm{pellet}}/L_{\mathrm{pellet}})} + N^4_{\mathrm{TEG}} \tag{4}$$

$$T_5 = \frac{(T_5 - T_4)}{R^{\mathrm{TH}}_{\mathrm{TEG}}(T_4, T_5, N_{\mathrm{pair}}, A_{\mathrm{pellet}}/L_{\mathrm{pellet}})} + \frac{(T_5 - T_6)}{R^4_{\mathrm{CNT}}} + N^5_{\mathrm{TEG}} \tag{5}$$

$$T_6 = \frac{(T_6 - T_0)}{R_{\mathrm{HS}}(T_6, T_0, N_{\mathrm{fins}})} + \frac{(T_6 - T_7)}{R_{\mathrm{LINK}}} + \frac{(T_6 - T_5)}{R^4_{\mathrm{CNT}}} \tag{6}$$

$$T_7 = \frac{(T_7 - T_3)}{R_{\mathrm{PART}}} + \frac{(T_7 - T_0)}{R_{\mathrm{HSTR}}} + \frac{(T_7 - T_0)}{R_{\mathrm{CNV}}(T_7)} + \frac{(T_7 - T_6)}{R_{\mathrm{LINK}}} \tag{7}$$

$$\begin{aligned} N^4_{\mathrm{TEG}} = {} & -\alpha\left(T_4, N_{\mathrm{pair}}, \frac{A_{\mathrm{pellet}}}{L_{\mathrm{pellet}}}\right) I T_4 \\ & + (1-\varepsilon) I^2 R^{\mathrm{EL}}_{\mathrm{TEG}}\left(T_{\mathrm{av}}, N_{\mathrm{pair}}, \frac{A_{\mathrm{pellet}}}{L_{\mathrm{pellet}}}\right) \\ & + \frac{\partial\alpha(T_4)}{2\partial T} I (T_4 - T_5) \end{aligned} \tag{8}$$

$$\begin{aligned} N^5_{\mathrm{TEG}} = {} & \alpha\left(T_5, N_{\mathrm{pair}}, \frac{A_{\mathrm{pellet}}}{L_{\mathrm{pellet}}}\right) I T_5 \\ & + \varepsilon \mathrm{I}^2 R^{\mathrm{EL}}_{\mathrm{TEG}}\left(T_{\mathrm{av}}, N_{\mathrm{pair}}, \frac{A_{\mathrm{pellet}}}{L_{\mathrm{pellet}}}\right) \\ & + \frac{\partial\alpha(T_5)}{2\partial T} I (T_4 - T_5) \end{aligned} \tag{9}$$

The most far-reaching assumption in the thermal model is that the interfaces of all elements are isothermal surfaces. In general this may be regarded as

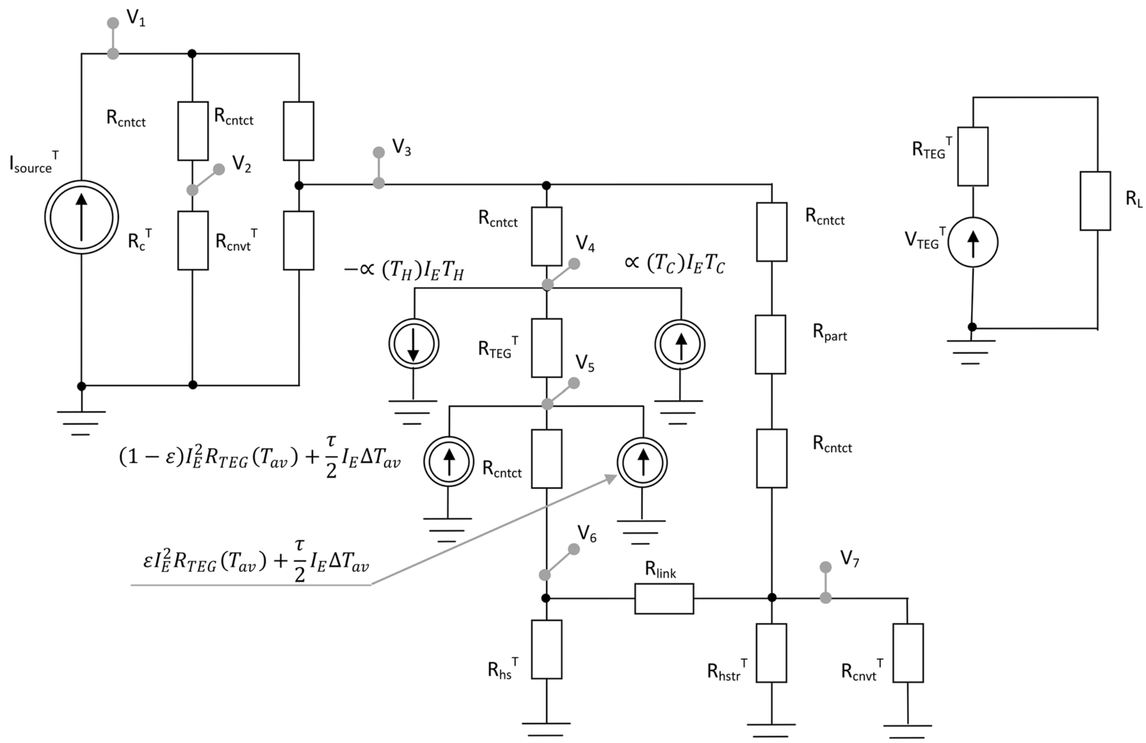

Fig. 3. Representation of the bearing as a resistive network with controlled current source components. The model includes thermoelectric modules. (The symbols are explained in the list of symbols or in Ref. 7).

true for elements of small dimensions and when the heat flow is perpendicular to the faces (no thermal gradients along the surface edges). Heat exchange in a thermoelectric module occurs only at the junctions which may lead to overestimation of the yield as a result of not taking conductive fillers between the pellets and radiative heat exchange into account.[9] Several distinct elements of the proposed model take different physical phenomena into account: thermoelectric conversion, natural convection (heat sink, flat surfaces) R_{CNVT}, convective boundary conditions at the rotating shaft R_{C}, internal bearing power loss I_{SOURCE}, and contact resistances R_{CNTCT}. The model adopted for the thermoelectric generator[10] is based on a thermal network including all thermoelectric effects (Seebeck (α), Peltier (αT), and Thomson (τ)) and including the overall effect of thermal resistance on generator structure. It does not, however, take into account module geometry or uneven temperature distribution on heat spreaders or internal thermal bridges. A heat-sink model (R_{HS}) and convection boundary conditions were considered by use of dimensional analysis and models described elsewhere.[11] As the properties of air change substantially with temperature, values from appropriate look up tables were used in model calculations. Convective heat transfer from a horizontal rotating cylinder has been described elsewhere.[12] Calculations of bearing thermal loss are based on the SKF model,[13] and used with the Walther viscosity model of grease as a lubricant.

The proposed model underwent sensitivity analysis to show which factors are most likely to affect harvested power levels. As a result the design variables were prioritized. It was shown that the power yield of the harvester strongly depends on the bearing type it operates on, because the power characteristics and contact resistances of bearings differ substantially.[14] In this work the model was used to calculate the maximum harvested power under maximum power transfer theorem conditions; it was also used with behavioral models of energy-management integrated circuits (IC).

EXPERIMENTAL VALIDATION

The possibility of energy harvesting on the basis of power thermal loss in a bearing was verified by comparing the experimentally obtained power gain of the harvester with power consumption by synthetic inductors measured by the authors and reported in the literature. The experimental results were compared with values obtained numerically to validate the numerical model.

The experimental setup is organized as shown in Fig. 4. The electric motor, 4, drives a two point supported shaft. The third bearing on the shaft, 2, can be moved so only radial load is applied to bearings 1 and 3, which were medium-sized typical steel self-aligning ball bearings (mean diameter 46 mm). The temperatures of the thermoelectric generator's (TEG) junctions, its open circuit voltage, and power available at the energy manager's output pin were measured under loads in the range 150–900 N and speeds in the range 500–3000 rpm (Fig. 5).

The power that could be harvested relative to the theoretical power loss in a bearing is presented in Fig. 6. The maximum available power is marked with a dashed line which shows interpolated measured data. The squares and stars show experimental measurements and numerical predictions, respectively. Because the voltage output of the generator ranges from 20 to 750 mV voltage level conversion and regulation are essential. Two different voltage converter and power-management systems were compared, the LTC3108 ultralow voltage step-up converter and power manager and the LTC3105 400-mA step-up DC/DC converter with maximum power point control and 250-mV start-up (both Linear Technology, Milpitas, CA, USA). The first of these devices enables energy conversion and storage starting with voltages as low as 20 mV; its conversion efficiency did not exceed 35% during the tests, however. The latter operates when the input voltage exceeds 250 mV and its conversion efficiency is in the range 40–90% for inputs of 0.25 V and 2.5 V, respectively. It is worth noting that conversion efficiency for the LTC3108 drops as the bearing loss rises. These efficiencies take voltage conversion, only, into account; TEG conversion efficiency is below 1% as is clearly apparent from Fig. 5.

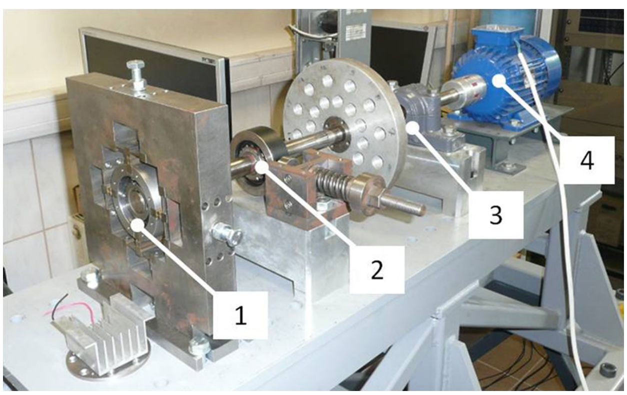

Fig. 4. Experimental setup: 1, bearing housing equipped with thermoelectric modules; 2, application of radial load; 3, bearing housing; 4, electric motor.

DISCUSSION OF RESULTS

Power levels were analyzed for continuous operation of the load, keeping operation of the harvester neutral. The assumed power consumption of the single synthetic inductance was 11 mW. Power levels appropriate for operation of the synthetic inductor circuitry are feasible for some loss of power in the bearing or with use of a larger number of generators. When coupled with only one thermoelectric generator operating at low temperature difference the LTC3108 can never supply the amount of energy required (Fig. 5). In contrast, sufficient energy is delivered by the LTC3105 when power loss in the bearing is approximately 16 W, which corresponds to a temperature difference of 4.18 K between the TEG's junctions for the example analyzed. The maximum temperature difference obtained in the experiments was 16 K (approximately 30 K between

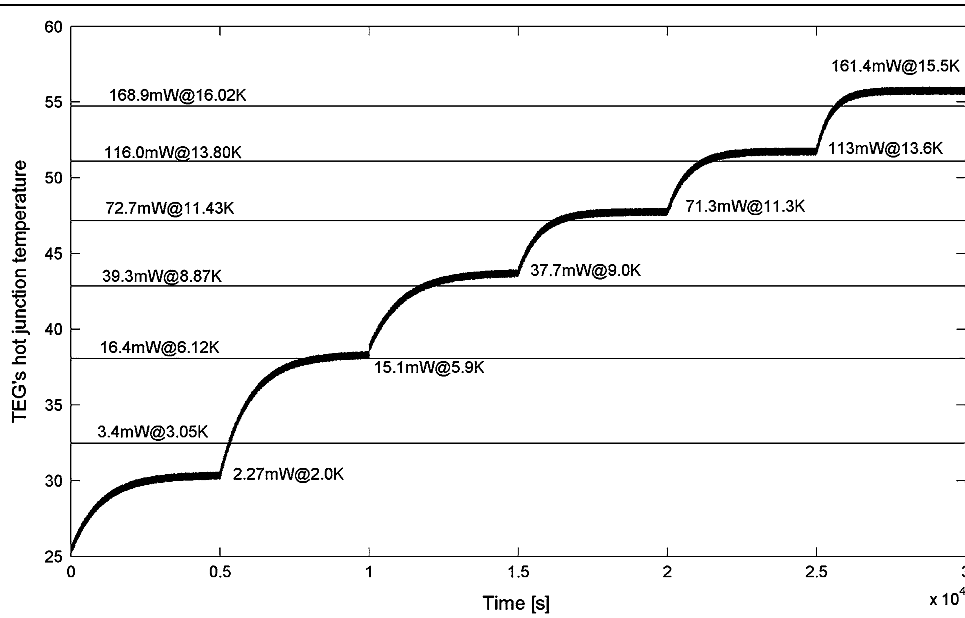

Fig. 5. Typical measured time series of the temperature of the TEG's hot junction. Horizontal lines show numerical predictions of this temperature in the steady state for each speed of rotation. The labels show the numerically obtained maximum and measured power levels for matched impedance conditions, and the corresponding temperature difference at the TEG's junctions. During experiments a constant radial load of 957 N was applied to the shaft and the speed of rotation was changed in the range 500–3000 rpm.

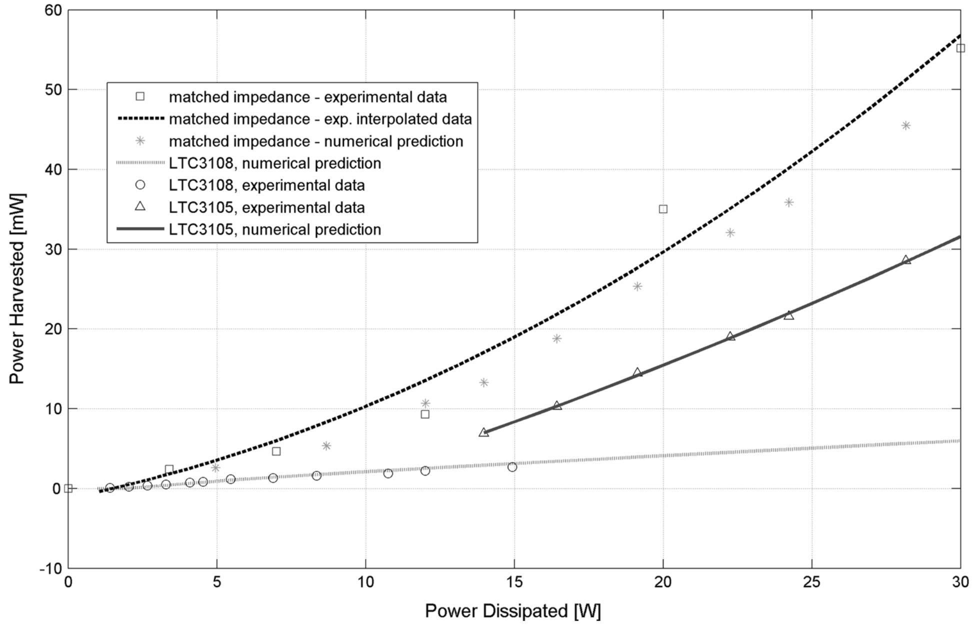

Fig. 6. Maximum harvested power (impedance matching) relative to the power dissipated in a bearing (squares and the dashed line indicate experimental results; the stars indicate numerical assessment), and usable power harvested during continuous operation with a step-up converter and power-management unit (circles and triangles indicate experimental results; the solid and dotted lines indicate numerical assessment).

the bearing and ambient temperature). One can easily cite applications for which both the absolute temperatures and the temperature difference are much higher. Nevertheless, every single application must be followed by careful study, to take into account details of bearing construction, the presence of other heat sources, the conductivity of the materials, heat bypasses, etc. Synthetic inductances based on operational amplifiers seem to be useless because their energy demand can be fulfilled only at the extremes of the chosen operating conditions. Accurate numerical prediction of both energy yield and temperature difference across the TEG's junctions is possible by use of the model (Fig. 6).

CONCLUSIONS

The concept of a semi-passive piezoelectric vibration damper powered by a thermoelectric source has been proposed. The main idea behind the proposed solution involves making a shunting circuit containing at least one synthetic inductor passive by delivering supply from a power harvester that operates on a bearing. The approach enables the shunted piezoelectric to operate under favorable conditions, because the synthetic inductor's resistance may be an order of magnitude lower than those of a typical coil inductor. The practical issue tackled by combining the shunt-damping technique with energy harvesting is elimination of the need for cabling by operating the shunt-damping treatment independently of the power source, so energy is harvested where it is actually used. The validity of the concept was proved experimentally by comparing the power consumption of synthetic inductors with results obtained during operation of a simple harvester. This revealed that a typical bearing during typical working conditions may be a source of sufficient energy for the harvester to operate. Nevertheless, two questions must be answered when designing a self-sufficient system:

- Is the transition through resonance during machine start-up an important issue? and
- Should the system be ready to operate from the beginning of machine operation?

If the answer to either of these questions is "yes" the thermoelectric harvesting unit should be appropriately oversized to ensure energy excess that can be stored in an energy buffer during normal operation of the machine and therefore be available at the next start-up. The possibility of powering synthetic inductors by using energy generated from thermal gradients results in piezoelectric vibration dampers that are more versatile in use and less bulky to implement. The proposed numerical model of a bearing could be used to predict the power gain with satisfactory accuracy.

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